SYSTEM AND METHOD FOR CONTROLLING PRESSURE IN REMOTE ZONES

Field of the Disclosure

[0001] The present disclosure relates generally to pressure control systems and, more particularly, to a system and a method for pressurizing and evacuating remote chambers or zones, such as remote zones found in semiconductor processing equipment. The remote zones may have rigid walls or flexible walls, and may be coupled or non-coupled.

Background of the Disclosure

[0002] Many machines and equipment include chambers, or zones that are pressurized or evacuated during operation of the equipment. As discussed herein, a zone is equivalent to an enclosed volume. The remote zones may have flexible walls or rigid walls and, may be coupled or non-coupled to each other.

[0003] The coupling between the various zones can comprise volumetric coupling that occurs when the zone walls are flexible and one zone expands and pushes against another zone. Outlet coupling occurs if a vacuum pressure connected to the zones drifts, causes outlet flows to change and results in flows transitioning. Inlet coupling occurs when there is a significant in-rush of flow into a manifold resulting in a drop of line pressure (transient behavior) that affects all the other zones fed by the same source.

[0004] Chemical mechanical polishing (CMP) machines are examples of machines that include zones that are pressurized or evacuated during use. CMP is a method of planarizing substrates, particularly silicon wafers, as part of semiconductor manufacturing processes. Such substrates are generally formed by the sequential deposition of conductive, semiconductive or insulative layers, and subsequent etching of the layers to create circuitry features. As a series

of layers are sequentially deposited and etched, the outer or uppermost surface of the substrate becomes increasingly non-planar. There is a need, therefore, to periodically planarize the substrate surface.

[0005] The planarization method typically requires that the substrate be mounted on a carrier or polishing head of a CMP machine. The exposed surface of the substrate is placed against a rotating polishing pad of the carrier head, and the carrier head provides a controllable pressure on the substrate to push it against the polishing pad. A polishing slurry, including at least one chemically-reactive agent and, in some cases, abrasive particles, is supplied to the surface of the rotating polishing pad.

[0006] Internal chambers or zones of a typical carrier head are formed at least in part by resilient bladders which expand upon the zones being pressurized and which contract upon a vacuum being created by evacuation within the zones. For example, pressurizing a zone in the carrier head can be used to press a substrate against a rotating polishing pad, while creating a vacuum in the zone can be used to provide suction for holding the substrate against the carrier head during transfer of the substrate to and from the polishing pad. The pressure in each zone can be controlled such that the polishing pad applies a desired force on the substrate held by the carrier head.

[0007] A pneumatic control system for controlling pressure within the remote zones of the carrier head can include flow control lines having pressure transducers and controllable valves. The flow control lines of the pneumatic control system may be connected to the zones of the carrier head through relatively long tubing, e.g., one meter or more. The pneumatic control system connects the zones of the carrier head to at least one vacuum source and at least one pressure source, and is appropriately connected to a computer that is programmed to receive measurements from the pressure transducer, and command the valves to alternatively

connect the remote zones of the carrier head to the vacuum source and the pressure source and, thus, pneumatically power the carrier head.

[0008] One problem associated with the pneumatic control system of the prior art is that the system relies solely on the pressure measured by the transducers placed in the flow control lines of the pneumatic control system. The transducers can only measure the pressure in the system and not in the remotely connected zones of the carrier head. As a result, the control system assumes that the pressures in the pneumatic control system are the same as that in the remotely connected zones of the carrier head. Such is clearly not the case, however, when localized pressure transients occur in the pneumatic control system, which leads to severe degradation of system performance.

[0009] What is still desired, therefore, is a new and improved pressure control system and method, which can be used for, but is not limited to, pressurizing and evacuating remotely connected zones, such as the chambers of a CMP carrier head, and that compensates for pressure measurements taken in lines remotely connected to the zones. Preferably, the new and improved pneumatic control system can be used for pressurizing and evacuating a multi-zone system, wherein the zones possess rigid or flexible walls, and wherein the zones are coupled or non-coupled.

Summary of the Disclosure

[0010] The present disclosure provides a model-based pressure observer that can be used with in any pressure control solution for a multi-zone system, where the number of zones can vary from $i=1$ to N. Furthermore, these zones may possess rigid or flexible walls and the zones may be coupled or non-coupled.

[0011] According to one exemplary embodiment of the present disclosure, a system for controlling fluid flow through i lines, wherein the i lines are connectable through tubing to i

zones, respectively, and wherein $i = 1, 2, \ldots, N$, is provided. The system includes at least one valve and a pressure transducer in each of the i lines, a control device for controlling the valves, and a zone pressure estimator for estimating pressures in the i zones.

[0012] The zone pressure estimator is connected to the pressure transducers and a first input device and is programmed to, receive a measured pressure (P_b) in the flow line from the pressure transducer, receive from the first input device constants ($C_{tube,i}$ and $\tau_{tube,i}$) associated with the tubing connecting the lines to the zones, a volume ($V_{z,i}$) of each zone, an initial volume ($V_{z0,i}$) of each zone under standard temperature and pressure (STP) conditions, a volume expansion/contraction time constant (τ_v), an expansion/contraction coefficient (γ_{ii}) of zone i, and a coupling coefficient (γ_{ij}) between zone i and zone j, and calculate an nth sample of an estimated pressure of the zone i, where n is time dependent and the estimated pressure is calculated according to equations described in detail below.

[0013] The control device is connected to the valves of the lines, the zone pressure estimator and a second input device. The control device is programmed to receive an nth pressure set point for each of the i zones from the second input device, and receive the nth sample of the estimated pressure for each of the i zones from the zone pressure estimator. The control device is also programmed to compare the nth pressure set point for each of the i zones to the nth sample of the zone pressure estimate, and, if the nth sample does not equal the nth set point, operate the valve until the sample equals the set point.

[0014] According to one aspect of the present disclosure, all the zones of the multi-zone system are fed by a single source and dump into a single vacuum exhaust, volumes of the zones can expand and contract, and the volumes of the zones interact with (push against) each other.

[0015] Among other aspects and advantages of the present disclosure, the system can be used for, but is not limited to, pressurizing and evacuating remotely connected, multiple

zones, such as the chambers of a CMP carrier head. The system compensates for pressure measurements taken in lines remotely connected to the zones, and can be used for pressurizing and evacuating a multi-zone system, wherein the zones possess rigid or flexible walls, and wherein the zones are coupled or non-coupled.

[0016] Additional aspects and advantages of the present disclosure will become readily apparent to those skilled in this art from the following detailed description, wherein an exemplary embodiment of the present disclosure is shown and described, simply by way of illustration. As will be realized, the present disclosure is capable of other and different embodiments and its several details are capable of modifications in various obvious respects, all without departing from the disclosure. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

Brief Description of the Drawings

[0017] Reference is made to the attached drawings, wherein elements having the same reference characters represent like elements throughout, and wherein:

[0018] FIG. 1 is a diagram illustrating an exemplary embodiment of a system and method, constructed in accordance with the present disclosure, for controlling a pneumatic control system connecting a vacuum source and a pressure source to remote zones of a machine, such as a chemical-mechanical planarization (CMP) machine;

[0019] FIG. 2 is a diagram of an exemplary embodiment of a manifold of the system of FIG. 1, including flow control lines shown connecting the vacuum and the pressure sources to the remote zones, which, in the exemplary embodiment shown, are coupled among each other;

[0020] FIG. 3 is a side elevation view, partially in section, of an example of a CMP machine including remote zones connected through a rotary union to the pneumatic control system of FIG. 1; and

[0021] FIGS. 4 through 7 are graphs illustrating pressure response times for various volumes and pressures for the pneumatic control system of FIG. 1, and a pneumatic control system of the prior art.

Detailed Description of Exemplary Embodiments

[0022] FIG. 1 shows an exemplary embodiment of a system 100, constructed in accordance with the present disclosure, for controlling a pneumatic manifold 110 connecting a vacuum source 30 and a pressure source 40 to remote zones Z_i of a machine, such as a chemical-mechanical planarization (CMP) machine 10, where $i = 1$ to N. The zones Z_i may possess rigid or flexible walls, and the zones Z_i may be coupled or non-coupled.

[0023] In addition to the manifold 110, the system 100 of FIG. 1 includes a zone pressure estimator 120, and a control device 130. The zone pressure estimator 120 and the control device 130 both comprise computers which may be provided separately or may be provided as an integrated unit. For example, the zone pressure estimator 120 of the present disclosure may be provided as a separate device and added to an existing pressure control system as an "aftermarket" piece, or could be provided as an integrated unit with the control device 130 in a newly manufactured pressure control system.

[0024] As shown in FIG. 2, the system manifold 110 includes flow control lines "b_i" where $i =1$ to N and corresponds to the number of remote zones Z_i. The flow control lines b_i are connected between an inlet manifold "L" and a manifold "man" having a venturi, and connect the vacuum source 30 and the pressure source 40 to the remote zones Z_i. Each flow control line b_i includes an inlet valve 112 for connecting the pressure source 40 to the remote

zones Z_i, a pressure transducer 114 for measuring the pressure in the flow control lines b_i, and an outlet valve 116 for connecting the remote zones Z_i to the vacuum source 30.

[0025] The zone pressure estimator 120 of FIG. 1 is programmed to receive pressure measurements from the transducers 114 of the system manifold 110, as shown in FIG. 2, and receive physical parameters of the system 100. The physical parameters may be entered through a first input device 122, as shown in FIG. 1, by an operator. The input device 122 can comprise a keyboard, a mouse and a monitor, for example. The zone pressure estimator 120 is further programmed to use the pressure measurements and the physical parameters to calculate and provide pressure estimates for each zone Z_i using an algorithm described in greater detail below.

[0026] The system control device 130 of FIG. 1 is programmed to receive the zone pressure estimates from the zone pressure estimator 120, and receive pressure set points for each of the remote zones Z_i, and use the zone pressure estimates and the pressure set points to control the valves 112, 116 of the system manifold 110, as shown in FIG. 2. The pressure set points can be entered by an operator using a second input device (or the first input device) and/or can be entered by a control device 20 of the processing machine 10, as shown in FIG. 1.

[0027] In the exemplary embodiment of FIG. 2, all the zones Z_i are fed by a single pressure source 40 and dump into a single vacuum exhaust 30. The remote zones Z_i have volumes that can expand and contract, and the volumes of the zones Z_i interact with (push against) each other.

[0028] As an example of a use for the system of the present disclosure, FIG. 3 shows the pneumatic control system 100 of FIG. 1 connected to a rotary union 18 of carrier head 16 of a CMP machine 10. The carrier head 16 independently rotates about its own axis, and has a carrier drive shaft 12 connecting a rotation motor 14 to the carrier head 16. The rotary union

18 at the top of the drive motor 14 couples fluid lines F_i to channels C_i in the drive shaft 12 where i =1 to N, corresponding to the number of remote zones Z_i. The channels C_i are in turn connected respectively to the remote zones Z_i contained in the carrier head 16.

[0029] Although not explicitly shown, the remote zones Z_i of the carrier head 16 are formed at least in part by resilient bladders which expand upon the zones Z_i being pressurized and which contract upon a vacuum being created within the zones Z_i. For example, pressurizing a zone Z_i in the carrier head 16 can be used to press a substrate against a rotating polishing pad, while creating a vacuum in the zone Z_i can be used to provide suction for holding the substrate against the carrier head 16 during transfer of the substrate to and from the polishing pad. Furthermore, the pressure in each zone Z_i can be controlled such that the polishing pad applies a desired force of the substrate held by the carrier head 16. The pneumatic control system 100 connects the fluid lines F_i extending from the rotary coupling 18 to the vacuum source 30 and the pressure source 40, and the control device 130 of the system 100 is programmed to operate the controllable valves 112, 116 to alternatively connect the remote zones Z_i of the carrier head 16 to the vacuum source 30 and the pressure source 40 and, thus, pneumatically power the carrier head 16.

[0030] One problem associated with a pneumatic control system of the prior art is that the system relies solely on the pressure measured by the transducers 114 placed in the flow control lines b_i of the manifold 110. The transducers 114 in the flow control lines b_i, however, can only measure the pressure in those lines and not in the remotely connected zones Z_i of the carrier head 16. As a result, the control system 130 assumes that the pressures in the flow control lines b_i are the same as that in the remotely connected zones Z_i of the carrier head 16. Such is clearly not the case when localized pressure transients occur in the flow control lines b_i, which can lead to severe degradation of system performance.

[0031] The present disclosure provides a new and improved pressure control system 100, which can be used for, but is not limited to, pressurizing and evacuating remotely connected zones Z_i of semiconductor processing equipment, such as a CMP carrier head 16 for example, and that compensates for pressure measurements taken in the flow control lines b_i remotely connected to the zones Z_i. The new and improved pneumatic control system 100 can be used for pressurizing and evacuating a multi-zone system where the number of zones Z_i can vary from $i=1$ to $i=N$. In addition, the new and improved pneumatic control system 100 can be used with remotely connected zones Z_i possessing rigid or flexible walls, and that are coupled or non-coupled to each other.

[0032] The coupling between the various zones Z_i can occur in three ways. Volumetric coupling at the zone occurs due to the volume expansion/contraction and volume-to-volume interaction. The interaction, for example, would occur by one zone expanding and pushing against another zone thereby increasing pressure within the second zone. In this case, the zone walls are flexible (and can expand and contract).

[0033] Outlet coupling at the exhaust occurs if the vacuum pressure level drifts causing outlet flows to change and in extreme cases results in flows transitioning between choked and unchoked. This is especially critical in the case of a venturi pump with high flow being dumped into the venturi line. In this case, the zone walls may be rigid or flexible.

[0034] Inlet coupling occurs if the set point in one zone is set sufficiently high such that there is a significant in-rush of flow into its manifold resulting in a drop of line pressure (transient behavior). This line pressure drop would affect all the other zones fed by the source. Again, the zone walls may be rigid or flexible.

[0035] It should be noted that a system with only one zone and rigid walls would be considered as a "non-coupled, single-zone system." Multiple instances of such a rigid zone that

are fed by independent inlets and that dump into independent exhausts would be an example of a "non-coupled, multi-zone system." A single zone with flexible walls that can expand or contract would be considered to be a "coupled, single-zone system." The system 100 represented in FIGS. 1 and 2 is a "coupled, multi-zone system," where the level of coupling can be quantified based on inlet, outlet, and volumetric coupling.

[0036] The zone pressure estimator 120 is used to estimate the pressure in each of the zones Z_i by using the pressure measurements of the transducers 114 in the system manifold 110, the physical parameters of the system 100, and a model-based algorithm to accurately estimate the pressure of the zones Z_i. As a direct consequence, a control system 100 that uses the zone pressure estimator 120 in a closed loop for controlling the pressure in the zones Z_i overcomes localized pressure transients in the system manifold 110 that may not occur in the zones Z_i themselves and, therefore, has significantly improved closed-loop control performance.

[0037] In addition, the zone pressure estimator 120 easily integrates into an advanced control system, and compensates for multiple zones Z_i that exhibit static and/or dynamic coupling of inlet pressure/flow, outlet pressure/flow, and zone volume interaction. The zone pressure estimator 120 places no restrictions on the size of the remotes zones Z_i. The zone pressure estimator 120 also can be used with zones Z_i that have fixed/rigid walls as well as zones with flexible walls. The zone pressure estimator 120 is valid for different ranges of pressure set points and, when incorporated into an advanced control system, will ensure consistent transient and steady-state behavior.

[0038] The model-based algorithm used to operate the zone pressure estimator 120 is based upon the dynamics of the system manifold 110, and the dynamics and volumetric coupling of the remote zones Z_i.

System Manifold Dynamics

[0039] The effective pressure inside each flow line b_i of the system manifold 110 is defined as:

$$\frac{dP_{b,i}}{dt} = \frac{P_{STP}}{V_{b,i}}(Q_{in,i} - Q_{o,i} - Q_{z,i}) \quad \forall i = 1,2,\ldots,N, \tag{1}$$

[0040] where $P_{b,i}$ is the pressure measured by the transducer 114 in the measurement chamber for the i^{th} zone, P_{STP} is the pressure at standard temperature and pressure (STP) conditions, $Q_{in,i}$ denotes the input flow and $Q_{o,i}$ and $Q_{z,i}$ denote the output flows. Specifically, $Q_{o,i}$ is the flow from the i^{th} flow line b_i to the venturi manifold, and $Q_{z,i}$ is the flow to the i^{th} zone. In (1), $V_{b,i}$ denotes the flow line b_i volume for the i^{th} zone.

[0041] The output flow to the venturi manifold "man" can be represented as:

$$Q_{o,i} = f(P_{b,i}, P_{man}, d_{orifice,i}) \quad \forall i = 1,2,\ldots,N, \tag{2}$$

[0042] where $d_{orifice,i}$ denotes the diameter of the fixed orifice in the measurement flow line b_i that feeds the venturi manifold and P_{man} denotes the pressure in the venturi manifold connected to the vacuum pump 30. It should be noted that the flow through the orifice may be choked or unchoked depending on the pressure differential across the fixed orifice.

Zone Dynamics and Volumetric Coupling

[0043] The flow to each zone Z_i can be described by the following dynamic equation (derived from the Navier-Stokes equations):

$$\frac{dQ_{z,i}}{dt} = (P_{b,i} - P_{z,i})C_{tube,i} - \frac{Q_{z,i}}{\tau_{tube,i}} \qquad \forall i = 1,2,\ldots,N, \tag{3}$$

[0044] where $Q_{z,i}$ and $P_{z,i}$ denote the inlet flow to and the pressure in the i^{th} zone, respectively, and $C_{tube,i}$ and $\tau_{tube,i}$ are constants associated with the tubing from the measurement flow line b to the zone Z_i.

[0045] The pressure dynamics within each zone Z_i can be described as follows:

$$\frac{dP_{z,i}}{dt} = \frac{P_{STP}}{V_{z,i}} Q_{z,i} - \frac{P_{z,i}}{V_{z,i}} \frac{dV_{z,i}}{dt}, \tag{4}$$

[0046] where the volume of each zone Z_i is denoted by $V_{z,i}$ and the dynamic volume interaction due to the coupling between the multiple zones Z_i can be mathematically described as follows:

$$\tau_v \frac{dV_{z,i}}{dt} + V_{z,i} = \left[V_{Z0,i} + \gamma_{ii}(P_{z,i} - P_{STP}) + \sum_{i \neq j} \gamma_{ij}(P_{z,i} - P_{z,j}) \right], \tag{5}$$

[0047] where $V_{z0,i}$ is the initial volume of each zone under standard temperature and pressure (STP) conditions, τ_v is the volume expansion/contraction time constant, and γ_{ii} represents the expansion/contraction coefficient, and γ_{ij} represents the coupling coefficient between zone i and zone j. It should be noted that mass/inertial effects are assumed to be negligible (hence, there is no acceleration term).

Zone Pressure Estimator

[0048] The control objective is to regulate the pressures within the remote zones Z_i. However, the pressure transducer 114 is housed in the flow line b of the system manifold 110 (as opposed to the zone). As seen in FIG. 1, the system manifold 110 is separated from the remote zones Z_i by long tubes F_i.

[0049] One solution is to rewrite the zone flow equation (3) in its discrete form:

$$\hat{Q}_{z,i}^{(n)} = \frac{\hat{Q}_{z,i}^{(n-1)} + \Delta t C_{pipe,i}(P_{b,i}^{(n)} - \hat{P}_{z,i}^{(n-1)})}{\left(1 + \frac{\Delta t}{\tau_{pipe,i}}\right)} \tag{6}$$

[0050] where $\hat{Q}_{z,i}^{(n)}$ denotes the n^{th} sample of the flow *estimate* to the i^{th} zone. It should be noted that P_b is the pressured measured by the flow line pressure transducer 114.

[0051] A discrete solution for the expression in (5) is then obtained as follows:

$$\hat{V}_{z,i}^{(n)} = \frac{\hat{V}_{z,i}^{(n-1)} + \frac{\Delta t}{\tau_v}\left[V_{z0,i} + \gamma_{ii}(\hat{P}_{z,i}^{(n-1)} - P_{STP}) + \sum_{i \neq j} \gamma_{ij}(\hat{P}_{z,i}^{(n-1)} - \hat{P}_{z,j}^{(n-1)})\right]}{\left(1 + \frac{\Delta t}{\tau_v}\right)}, \tag{7}$$

[0052] where $\hat{V}_{z,i}^{(n)}$ denotes the n^{th} sample of the volume estimate to the i^{th} zone. Based on equations (4), (6) and (7), the algorithm of the pressure estimator 120 is constructed as follows:

$$\hat{P}_{z,i}^{(n)} = \hat{P}_{z,i}^{(n-1)} + \Delta t\left(\frac{P_{STP}}{\hat{V}_{z,i}^{(n)}}\hat{Q}_{z,i}^{(n)} + \frac{\hat{P}_{z,i}^{(n-1)}}{\tau_v \hat{V}_{z,i}^{(n)}}\left[\hat{V}_{z,i}^{(n)} - V_{z0,i} - \gamma_{ii}(\hat{P}_{z,i}^{(n-1)} - P_{STP}) - \sum_{i \neq j}\gamma_{ij}(\hat{P}_{z,i}^{(n-1)} - \hat{P}_{z,j}^{(n-1)})\right]\right), \tag{8}$$

[0053] where $\hat{P}_{z,i}^{(n)}$ denotes the nth sample of a pressure estimate of the i^{th} zone, $\hat{Q}_{z,i}^{(n)}$ is obtained from the flow estimate defined in (6) or can be replaced by the direct flow measurement Q_z when available, and $\hat{V}_{z,i}^{(n)}$ is obtained from (7).

[0054] For a fixed volume (i.e., rigid walls) that by construction does not exhibit volume expansion and hence, exhibits no volumetric coupling $\gamma_{ij} = 0 \forall i, j = 1,2,\ldots,N$. As a result, the expression in (5) reduces to $V_{z,i} = V_{z0,i}$ and $\hat{V}_{z,i}^{(n)} = V_{z0,i} \forall n$. Thus, from (8), the estimated pressure $\hat{P}_{z,i}^{(n)}$ for a fixed volume with rigid walls can be rewritten as follows:

$$\hat{P}_{z,i}^{(n)} = \hat{P}_{z,i}^{(n-1)} + \Delta t \frac{P_{STP}}{V_{Z0,i}} \hat{Q}_{z,i}^{(n)} \tag{9}$$

[0055] It should be noted that the discrete implementations of the estimator equations may be explicit or implicit and do not have any discernable impact on system performance so long as the discrete implementations satisfy well-known stability conditions.

<u>Control Algorithm</u>

[0056] To validate the performance of the zone pressure estimator 120, the calculations defined in (6), (7), and (8) were integrated into a control algorithm programmed into the zone pressure estimator 120 and the following experiments were performed using the system 100 shown in FIG. 1, and a system constructed in accordance with the prior art (i.e., not including the zone pressure estimator 120). From FIGS. 4 through 7, it is clearly shown that the steady-state performance, as represented by lines "X" of the estimator-based control device 100 of

FIG. 1 is significantly better than the steady-state performance, as represented by lines "Y" of a system constructed in accordance with the prior art for a range of volumes and pressure set points in that, the estimator-based control device 100 produces negligible oscillations and much smaller steady-state offset.

[0057] An example of the system parameters for remote zones Z_i connected to respective measurement chambers by a tube length of 1.2 m with a 4 mm inner diameter for N_2 (nitrogen) are listed below:

P_{STP}	= 14.7 psia	pressure at STP conditions
ρ_{STP}	= 1.16 kg/m^3	density at STP conditions
γ	= 1.4	specific heat ratio
T_I	= 300° K	operating temperature
R	= 297 J/kg-K	ideal gas constant
μ	= 1.77×10^{-4} poise	coefficient of viscosity
C_{tube}	≈ 65400 kg/cc	tube parameter
τ_{tube}	≈ 3 ms	tube time constant

[0058] The control device 130 is connected to the valves 112, 116 of the lines b_i, the zone pressure estimator 120 and a second input device, such as the control device 20 of the CMP machine 10. In general, the control device 130 is programmed to, receive the *n*th pressure set point for each of the *i* zones from the second input device 20, receive the *n*th sample of the zone pressure estimate for each of the *i* zones from the zone pressure estimator 120, and compare the *n*th pressure set point for each of the *i* zones to the *n*th sample of the zone pressure estimate, and, if the sample does not equal the set point, operate the valves 112, 116 until the sample equals the set point.

[0059] The present disclosure, therefore, provides a new and improved pneumatic control system 100 that can be used for, but is not limited to, pressurizing and evacuating remotely connected volumes of semiconductor processing equipment, such as a CMP carrier head 10 for example, and that compensates for pressure measurements taken in chambers

remotely connected to the volume. In addition, the pneumatic control system 100 of the present disclosure can be used for pressurizing and evacuating a multi-volume system were the number of volumes or zones can vary from $i = 1$ to $i = N$, wherein the zones possess rigid or flexible walls, and wherein the zones are coupled or not coupled to each other.

[0060] It should be understood that the present disclosure is directed to the pneumatic control system 100 that can be used with or as part of a CMP machine. The pneumatic control system 100 of the present disclosure, however, is not limited to being used with or part of a CMP machine, and the pneumatic control system 100 can be used with remote zones of pneumatically operated machines, devices or uses, other than a CMP machine.

[0061] The exemplary embodiments described in this specification have been presented by way of illustration rather than limitation, and various modifications, combinations and substitutions may be effected by those skilled in the art without departure either in spirit or scope from this disclosure in its broader aspects and as set forth in the appended claims.